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WEAK DECAYS OF CHARM HADRONS: THE NEXT LESSON ON QCD – AND POSSIBLY MORE![1]

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Abstract

Second-generation theoretical technologies – heavy quark expansions, QCD sum rules and QCD simulations on the lattice – are arriving on the scene, allowing a treatment of charm decays that is genuinely based on QCD. The availability of those theoretical tools strengthens the case for the need for comprehensive precision measurements of charm decays. It is pointed out that the decays of charm mesons as well as of charm baryons have to be systematically analysed to gain control over theoretical uncertainties. A τ-charm factory with $E_{c.m.} \leq 5.5$ GeV is optimally suited for such a program. It would lead to a deeper understanding of QCD that would also prepare us better for exploiting the discovery potential anticipated in beauty decays. In addition it is quite conceivable (though certainly not guaranteed) that there arise fundamental surprises, such as non-canonical rare D decays, D^0-$\bar{D}^0$ oscillations and CP violation in charm decays which would dramatically alter our perspective on Nature's fundamental forces.

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1 INTRODUCTION

An instructive global perspective on the forces controlling the weak decays of charm hadrons can be gained by considering their lifetime ratios [1]:

$$\frac{\tau(D^+)}{\tau(D^0)} \simeq 2.50 \pm 0.05 \ , \quad \frac{\tau(\Xi_c^+)}{\tau(\Xi_c^0)} \simeq 4.0 \pm 1.5 \tag{1}$$

$$\frac{\tau(D_s)}{\tau(D^0)} \simeq 1.13 \pm 0.05 \ , \quad \frac{\tau(\Xi_c^+)}{\tau(\Lambda_c)} \simeq 2.0 \pm 0.7 \tag{2}$$

$$\frac{\tau(\Lambda_c)}{\tau(D^0)} \simeq 0.51 \pm 0.05 \ , \quad \frac{\tau(D^+)}{\tau(\Xi_c^0)} \simeq 10 \pm 2.5 \tag{3}$$

The *qualitative* pattern in these ratios can be readily understood by realizing that destructive interference (and to a lesser degree 'Weak Annihilation') affects meson lifetimes whereas baryon lifetime ratios are shaped by the interplay of 'Weak Scattering' and destructive as well as constructive interference. Yet a pessimist looks at these numbers, realizes that the non-perturbative corrections that distinguish the various decay rates are large, that everything is rather involved, and concludes that no quantitative insight can be gained here. An optimist on the other hand observes that these non-perturbative effects – while certainly large – are not of an overwhelming size: only the extreme ratio between the longest- and the shortestlived charm hadron amounts to an order of magnitude. Furthermore there are so many transitions [4] that a theoretical description that might be of uncertain validity when applied to a single decay class will be cross-checked in many highly non-trivial ways. The optimist thus looks at charm decays as a unique opportunity to be educated about the workings of QCD in a novel environment – and that is the attitude that I am going to advocate here.

This optimism is fed by the timely emergence and increasing maturity level of second-generation theoretical technologies applicable here, namely

- treatments based on QCD sum rules;
- expansions of the transition amplitudes in powers of $1/m_Q$, m_Q being the heavy flavour quark mass;
- numerical simulations of QCD on a lattice.

These methods are to be seen as complementing each other rather than competing against each other. To cite but one example: lattice simulations are just now reaching a level where charm decays can be tackled [2], whereas a treatment of beauty decays will remain beyond our reach still for some time to come; $1/m_Q$ expansions on the other hand can be expected to be well behaved for beauty decays since $\mu_{had}/m_b \ll 1$, while in charm decays terms that are formally of higher order in $1/m_c$ might turn out to be numerically important. A detailed study of charm decays then serves a dual purpose: (i) They provide a common arena for probing different theoretical technologies. (ii) Theoretical predictions based on $1/m_Q$ expansions have to be viewed a priori as not better than semi-quantitative in charm decays; yet their confrontation with detailed data will allow us to infer the weight of different non-perturbative corrections in charm decays and extrapolate them to beauty decays.

The remainder of this talk will be organized as follows: in Sect. 2 I sketch a description of inclusive charm decays that is intrinsically connected with QCD; in Sect. 3 I address exclusive non-leptonic two-body decay modes; in Sect. 4 I briefly discuss rare charm decays before presenting a summary in Sect. 5.

[4] In addition to lifetimes there are semileptonic branching ratios and lepton energy spectra as will be discussed later.

2 INCLUSIVE HEAVY-FLAVOUR DECAYS

The widths for the weak decays of heavy-flavour hadrons H_Q into an inclusive final state f can be calculated in QCD as an expansion in powers of $1/m_Q$ [3, 4]:

$$\Gamma(H_Q \to f) = \frac{G_F^2 m_Q^5}{192\pi^3}|KM|^2[c_3(f)\langle H_Q|\bar{Q}Q|H_Q\rangle + c_5(f)\frac{\langle H_Q|\bar{Q}i\sigma \cdot GQ|H_Q\rangle}{m_Q^2} +$$

$$+ \sum_i c_6^{(i)}(f)\frac{\langle H_Q|\bar{Q}\Gamma_i q\bar{q}\Gamma_i Q|H_Q\rangle}{m_Q^3} + \mathcal{O}(1/m_Q^4)] \qquad (4),$$

where the dimensionless coefficients $c_i(f)$ depend on the parton level characteristics of f and on the ratios of the final-state quark masses to m_Q; KM denotes the appropriate combination of weak mixing angles.

It is through the expectation values of the operators appearing on the right-hand side of eq. (4) that the dependence on the decaying *hadron* and on non-perturbative forces in general enters. Since these are on-shell matrix elements one sees that $\Gamma(H_Q \to f)$ is indeed expanded into a power series in μ_{had}/m_Q, as stated before. One can immediately read off an important qualitative result from eq. (4): there are *no* corrections of order $1/m_Q$ to *total* rates [although they emerge for lepton *spectra* [5]]. The leading non-perturbative corrections thus scale like $1/m_Q^2$, i.e. they fade away quickly with increasing m_Q.

While at present one is unable to determine the size of these matrix elements from first principles, one can relate them to other observables. The expectation value of the chromomagnetic operator $\bar{Q}i\sigma \cdot GQ$ can be extracted from the measured hyperfine splitting between the pseudoscalar and vector states:

$$< P_Q|\bar{Q}i\sigma \cdot GQ|P_Q > \simeq \frac{3}{2}(M_{V_Q}^2 - M_{P_Q}^2) \qquad (5)$$

with $V_Q = D^*[B^*]$ and $P_Q = D[B]$ for $Q = c[b]$. For the baryons Λ_Q, on the other hand, it vanishes:

$$< \Lambda_Q|\bar{Q}i\sigma \cdot GQ|\Lambda_Q > \simeq 0 \qquad (6)$$

The scalar operator $\bar{Q}Q$ can be expanded again into a series of inverse powers of m_Q:

$$< H_Q|\bar{Q}Q|H_Q >= 1 - \frac{< (\vec{p})^2 >}{2m_Q^2} + \frac{3}{8} \cdot \frac{M_{V_Q}^2 - M_{P_Q}^2}{m_Q^2} + \mathcal{O}(1/m_Q^3), \qquad (7)$$

where $< (\vec{p})^2 > /2m_Q \equiv < H_Q|\bar{Q}(i\vec{D})^2 Q|H_Q > /2m_Q$ denotes the expectation value for the kinetic energy of the heavy quark Q moving inside the hadron H_Q under the influence of the gluon background field. The first term on the right-hand side of eq. (7) reproduces the simple parton model result, i.e. the 'spectator ansatz' leading to universal lifetimes and semileptonic branching ratios for all hadrons of a given flavour Q; the first two terms then represent the mean value of the Lorentz time dilatation factor $\sqrt{(}1-v^2)$ that slows down the decay of the quark Q in a moving frame. The numerical size of $< (\vec{p})^2 >$ is not known yet. Results from two analyses based on QCD sum rules exist, though [6]; lattice simulations of QCD will be able to extract this quantity in the near future [5]; measuring the mass of Λ_b to 10 MeV accuracy will enable us to determine the difference of $< (\vec{p})^2 >$ for the heavy-flavour meson and baryon states.

The last term in eq. (4) incorporates the conventional non-spectator effects, namely 'Pauli Interference' and 'Weak Annihilation/Scattering' and thus generates lifetime differences between the different hadrons of a given heavy flavour.

The expansion parameter $\mu_{had}/m_b \sim 1/10$ for beauty decays is reasonably small and one can expect the first few terms in the expansion to yield a good approximation to the exact result; this also means that non-perturbative corrections are smallish in inclusive beauty decays. For charm decays on the other hand one finds $\mu_{had}/m_c \sim 0.3$. While this quantity is at least smaller than unity, it is not

[5] Lattice calculations will actually yield more directly $< H_c|\bar{c}c|H_c >$.

small. Contributions that are formally of higher order in $1/m_Q$ can then become numerically important. Therefore one expects to make predictions for charm decays that can at best claim semi-quantitative validity. Yet there is another – and I think more fruitful – perspective on this situation: charm decays serve as Nature's microscope, magnifying the non-perturbative corrections affecting beauty decays by factors $(m_b/m_c)^2 \sim 10$ and even $(m_b/m_c)^3 \sim 30$ [7]!

This situation can be illustrated by one topical example, namely the size of the semileptonic branching ratios. To leading order in $1/m_c$ one finds of course the parton model result $BR_{SL}(D) \sim 15\%$. The first non-perturbative correction arises on the $1/m_c^2$ level and reduces it considerably, yielding $BR_{SL}(D) \sim 10\%$ for D^0, D^+ and D_s mesons. To order $1/m_c^3$ one finally obtains a large splitting, namely $BR_{SL}(D^+) \sim 16\%$ and $BR_{SL}(D^0) \sim 8\%$. Clearly, on this level of the analysis there are large numerical uncertainties. Yet those can be brought under control once other observables have been measured and compared with the theoretical predictions, namely

- $BR_{SL}(D_s)$, $BR_{SL}(\Lambda_c)$ and $BR_{SL}(\Xi_c)$;
- the lepton spectra in the semileptonic decays of D^0, D^+, D_s, Λ_c and Ξ_c.

For it is the same set of operators, namely $\bar{c}c$, $\bar{c}i\sigma \cdot Gc$ and $(\bar{c}\Gamma_i q)(\bar{q}\Gamma_i c)$, that control all these processes through order $1/m_c^3$.

3 EXCLUSIVE NON-LEPTONIC TWO-BODY DECAYS

3.1 Phenomenological Models

Phenomenological descriptions of two-body modes for heavy-flavour hadrons were pioneered by the authors of ref. [8]. There are three main ingredients in such models: (i) One assumes factorization, i.e. one uses $< M_1 M_2 | J_\mu J_\mu | D > \simeq < M_1 | J_\mu | D > \cdot < M_2 | J_\mu | 0 >$ to describe $D \to M_1 M_2$. (ii) One employs one's favourite hadronic wavefunctions to compute $< M_1 | J_\mu | D >$. (iii) All two-body modes are then expressed in terms of two free fit parameters a_1 and a_2 with a_1 controlling the so-called "class I" $D^0 \to M_1^+ M_2^-$ and a_2 the "class II" $D^0 \to M_1^0 M_2^0$ transitions; both quantities contribute coherently to the "class III" $D^+ \to M_1^0 M_2^+$ transitions.

With these two free parameters a_1 and a_2 (and some considerable degree of "poetic license" in invoking strong final state interactions), one obtains a decent fit for the D^0 and D^+ modes. One has to point out, though, that this success is considerably helped by the merciful imprecision in some of the branching ratios measured so far.

Very recently Heavy Quark Symmetry and Chiral Symmetry (for the light quarks) have been incorporated into these models[9]; thus they have presumably reached their final level of maturity. To pass a final judgement on these phenomenological models requires an analysis

- that can rely on a host of well-measured modes, i.e. branching ratios that are measured to better than 10% accuracy,
- where final states with (multi)neutrals are included;
- that is performed for D_s, Λ_c and Ξ_c two-body channels as well and
- that treats Cabibbo-allowed, Cabibbo-suppressed and doubly-Cabibbo-suppressed decays separately.

It is quite likely – and actually I firmly expect – that such a comprehensive analysis, in particular for the a_2 transitions, will reveal serious and systematic deficiencies in these phenomenological models. To overcome those will require a description that is more firmly grounded in QCD. I will briefly comment on them below. However I would like first to stress what we have learnt and are still learning from the phenomenological treatments:

– They have yielded quite a few successful predictions in a "user-friendly" fashion, in particular also for B decays.

– They have helped us significantly to focus on the underlying theoretical problems, such as the question of factorization or the $1/N_C$ rule [10].

– They can provide us with valuable, albeit indirect, information on the strong final state interac-

tions. Such information is crucially important for deciding on the most promising strategy to search for CP violation in charm decays and then to interpret properly a signal that might be observed in the future. The so far most detailled attempt in this direction has recently been undertaken by the Rome-Napoli group [11]. The authors conclude that the typical scale for direct CP asymmetries in D decays is of order 10^{-3} – in agreement which general expectations stated a few years ago [12].

3.2 Theoretical Descriptions

The first treatment of charm two-body decays that is intrinsically connected to QCD was given by Blok and Shifman some time ago, based on QCD sum rules [13]. It would be desirable to have this analysis updated and refined, in particular by not imposing $SU(3)_{fl}$ symmetry.

The same two authors actually have moved into a different direction, namely to apply methods based on a heavy quark expansion to non-leptonic two-body modes of beauty [14]. I believe this ansatz promises to significantly advance our understanding of exclusive heavy flavour decays and thus deserves increased attention.

4 RARE DECAYS

There are five categories of rare decays that I would like to sketch.

4.1 Expected and Informative Decays

Doubly Cabibbo suppressed decays like $D^+ \to K^+\pi^0$ or $D^0 \to K^+\pi^-$ make up this category. The first clear evidence for them has been presented recently by the CLEO collaboration [15]:

$$\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = (0.77 \pm 0.25 \pm 0.25)\% \simeq 3 \cdot \tan^4(\theta_c) \tag{8}$$

in agreement with a prediction of $2 \cdot \tan^4(\theta_c)$ for this ratio [16].

4.2 Expected and Unexciting Decays

The mode $D^0 \to \bar{K}^{0*}\gamma$ can proceed by W exchange together with photon bremsstrahlung; a very rough order of magnitude estimate yields an expected branching ratio of $\sim \mathcal{O}(10^{-5})$. Seen by itself this mode is quite unremarkable. Yet its observation would serve an ulterior motive. For it has been suggested that the KM parameter $|V(td)|$ can be extracted from radiative B decays [17]: $BR(B \to \rho\gamma)/BR(B \to K^*\gamma) \simeq |V(td)|^2/|V(ts)|^2$ with $|V(ts)| \simeq |V(cb)|$. This is based on the assumption that both radiative transitions are dominated by the electromagnetic penguin operator. There is however a fly in the ointment for this interesting suggestion: also W exchange coupled with photon emission generates $B \to \rho\gamma$ transitions; yet this contribution is independant of $|V(td)|$ and a priori it could be comparable in size to the penguin-mediated $B \to \rho\gamma$. Ignoring such a contribution would lead to the extraction of an incorrect number for $|V(td)|$. Yet once the corresponding transition $D \to \bar{K}^{0*}\gamma$ has been measured, one can obtain a reliable estimate for the W exchange contribution to $B \to \rho\gamma$.

4.3 Unexpected and Exciting Decays

Non-minimal SUSY can generate $D^0 \to \rho\gamma$ with a branching ratio of $\sim 10^{-6}$ - 10^{-5} [18]. In addition, Weak Annihilation can also contribute with a branching ratio $\sim 10^{-6}$. Observing

$$\frac{BR(D^0 \to \rho^0\gamma)}{BR(D^0 \to \bar{K}^{0*}\gamma)} \neq \tan^2(\theta_c)$$

would, however, be evidence for the intervention of "New physics" like non-minimal SUSY.

4.4 Puzzling Decays

An observation of, for instance, $D^+ \to K^{*+}\gamma$ would be very puzzling. For one expects in the Standard Model: $BR(D^+ \to K^{*+}\gamma) \sim \tan^4(\theta_c) \cdot BR(D^0 \to \bar{K}^0\gamma) \sim 10^{-7}$; I have not found a reasonable New Physics scenario that would raise this number significantly.

4.5 "Shots In The Dark"

I have been unable so far to identify New Physics scenarios that would generate decays like $D \to \gamma\gamma$, γ + *nothing*, π/ρ + *nothing* on a level that could be observed at a τ-charm factory.

5 SUMMARY AND OUTLOOK

The defining goal in studies of the physics of charm decays is to probe and understand the strong interactions in a novel environment, namely at the interface between the short-distance and long-distance regime where the effects are numerically large, but not overwhelming. The prospects of reaching that goal have been enhanced considerably by the increasing maturity of second-generation theoretical technologies, namely heavy quark expansions, QCD sum rules, and QCD simulations on the lattice. Actually achieving it would be of significant intellectual value; in addition – and maybe even more important – it would sharpen our theoretical tools for dealing with beauty decays and fully exploiting the tremendous discovery potential there. For the non-perturbative corrections that have to be understood with high precision and reliability in beauty decays are quantitatively enhanced in charm decays; those act – as stated before – as a microscope.

To match these objectives the experimental program has to be based on the following elements:

• One has to determine some *absolute* branching ratios precisely, among them semileptonic branching ratios and lepton spectra.

• A detailed study of the *inclusive* semileptonic $c \to s$ and $c \to d$ decays is of particular value since it prepares us in an optimal way for dealing with semileptonic B decays at a beauty factory operating at threshold.

• A *large* body of well measured branching ratios – including for final states containing (multi)neutrals – has to be obtained.

• Such a comprehensive program has to be performed for D^0, D^+, D_s, Λ_c, Ξ_c^+, Ξ_c^0, and preferably also for Ω_c decays.

A τ-charm factory is optimally suited for this demanding program and one can thus state that **"The τ-charm factory is the QCD machine for the 90's!"**. From the program listed above it can be concluded that as far as charm physics is concerned

• one has to cross at least the $\Xi_c\bar{\Xi}_c$ and preferably the $\Omega_c\bar{\Omega}_c$ threshold, i.e. c.m. energies of 5–5.5 GeV have to be reached;

• one needs high luminosity; this is not based on the outlandish needs of a single measurement, but on the fact that D, D_s, Λ_c and Ξ_c decay studies cannot be done in a parasitic fashion, but require separate runs at different energy settings.

In my judgement it would be inappropriate to invoke searches for D^0–$\bar{D}^0$ oscillations, rare D decays and CP violation in charm decays as *primary* motivations for building a τ-charm factory of high luminosity. On the other hand they represent the "icing on the cake": There is a good chance that such "High Impact" physics will emerge in the charm sector; the high luminosity and purity of the data sample from a τ-charm factory will be critical in uncovering such a fundamental surprise.

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